Ultrafast thin-disk laser oscillators as driving sources for high harmonic generation

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Abstract. Thin-disk laser oscillators can nowadays reach few tens of femtosecond pulses at gigawatt and megahertz repetition rates becoming increasingly more powerful sources for intra-oscillator high harmonic generation (HHG). Currently, we can generate high harmonics in neon reaching photon energies of 70 eV, which we expect to increase toward 100 eV in the near future. In parallel, the achievable average and peak output powers of these oscillators in the range of 100 W and 100 MW, respectively, make these sources very promising to drive HHG in single-pass configuration after nonlinear pulse compression. Starting from transform-limited 30 to 50 fs soliton output soliton pulses of TDL oscillators, we will likely see these lasers approaching a single-cycle regime becoming highly attractive sources for attosecond science.

1 Introduction

Compact high harmonic generation (HHG) systems as affordable tabletop coherent XUV sources are becoming increasingly popular in the last years. The trend has been largely empowered by the progressing laser technology providing the required high-energy ultrafast pulses at increasing repetition rates, boosting the achievable XUV flux. Chirped-pulse fiber amplifier systems (FCPA) have been particularly successful in this direction. HHG system delivering 13.5 mW of XUV power at 13 eV at 1 MHz [1] as well as water window soft X-ray sources operating at 100 kHz [2] have been demonstrated based on FCPA. Toward even higher repetition rates, femtosecond enhancement cavities (fsEC) are commonly used, enabling to drive HHG at up to several hundred megahertz repetition rates [3]. A promising direction to further simplify the fsEC concept is based on driving HHG directly inside the cavity of an ultrafast laser oscillator [4]. Intra-oscillator HHG systems do not require coherent coupling into an external cavity, while being more tolerant to losses thanks to the presence of gain inside the cavity. Thin-disk laser (TDL) oscillators are particularly well suited for this task [5]. Compared to other Yb-based high-power laser technology, TDL oscillators reach very short pulse duration directly from the laser output. Already sub-30-fs pulses have been shown using a commercially available Yb:YAG gain material [6]. Additionally, the thin-disk geometry can withstand very high peak powers, up to ~2 GW inside the cavity have already been demonstrated in such oscillators [7,8].

The concept of HHG inside a TDL oscillator has been pioneered by our group since the last decade [9]. In this work we show the latest progress of our system when we reached a sufficiently high peak intensity inside the cavity to drive HHG in neon. We reached photon energies up to 70 eV, which we expect to increase to 100 eV in the near future. In parallel, we are planning to use the laser system

Fig. 1. Experimental setup of the intra-oscillator HHG system. The driving laser is a Kerr lens mode-locked TDL oscillator based on Yb:YAG gain material. The generation gas is injected into the laser using a 50 µm diameter nozzle and the XUV light is outcoupled from the oscillator using a pierced mirror (inset) with a 150 µm on-axis hole opening.

Intracavity performance:
- Peak power: 1.3 GW
- Pulse duration: 35 fs
- Average power: 1 kW
- Pulse energy: 50 µJ
- Repetition rate: 17 MHz
- HHG target gas: Neon
- Backing pressure: 10 bar
for driving HHG in single-pass configuration after nonlinear pulse compression. Previously we showed that our laser can deliver 5-µJ, 50-fs pulses at 100 W of average power, corresponding to 100 MW of peak power [10]. This is sufficiently high level to drive nonlinear pulse compression in a gas-filled multi-pass cell. According to our simulations we should reach down to ~8-fs compressed pulses within a single compression stage. We expect to have the first experimental results ready at the time of the conference.

2 Intra-oscillator HHG experiment

![Fig. 2. HHG spectrum generated in neon acquired by a flatfield XUV spectrometer.](image)

The experimental setup is shown in Fig. 1. The laser is a Kerr lens mode-locked (KLM) TDL oscillator based on an Yb:YAG gain material operating in a vacuum environment. It delivers 35-fs pulses at 17 MHz repetition rate. The neon gas is injected into the laser cavity using a 50-µm quartz nozzle at 10 bar of backing pressure. The XUV light generated at 1.3 GW of intracavity peak power. It is outcoupled from the laser cavity using a pierced mirror with an on-axis 150-µm-diameter opening and stripped of the residual infrared light using a pair of antireflection-coated grazing-incidence plates. The spectrum shown in Fig. 2 was acquired using a self-designed flatfield XUV spectrometer.

3 Nonlinear pulse compression

![Fig. 3.](image)

To reach even shorter pulse durations than directly accessible by TDL oscillators, we are planning to implement a nonlinear compression stage based on a gas-filled multipass cell operating in a net-negative dispersion regime. In Fig. 3 we show a numerical simulation of the spectral broadening in argon at 11 bars of pressure. Assuming a 50-fs 5-µJ input pulse we are expecting to reach sub-10-fs pulses within a single compression stage.

We are currently working on the experiment, and we should have the first experimental data available at the time of the conference.

4 Conclusions

We have presented the recent progress of our intra-oscillator HHG source. We have achieved a sufficiently high intensity inside the laser to drive HHG in neon and reached a photon energy cut-off of ~70 eV, which we expect to increase toward 100 eV in the near future. In parallel, we are working on a gas-based compression stage enabling HHG in a single-pass configuration. We expect to have the first experimental results ready at the time of the conference.

References

8. J. Fischer, J. Drs, M. Müller, N. Modsching, F. Labaye, V. J. Wittwer, and T. Südmeyer, in CLEO (2022), Paper SP4E.4